Nanobiochar: Properties, Preparation, Key features and its Impact on Soil and Crop Ecosystem

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ABSTRACT

Nano biochar, a carbon-rich material, is increasingly recognized for its pivotal role in sustainable agriculture and environmental management. It is produced through the pyrolysis of biomass under controlled conditions, converting organic matter into a stable form of carbon. This process effectively sequesters carbon and mitigates greenhouse gas emissions while yielding a valuable soil amendment. In agriculture, biochar offers multifaceted benefits. Its porous structure enhances soil fertility and water retention, fostering optimal conditions for plant growth. By serving as a reservoir for nutrients, biochar promotes their slow release, reducing the risk of leaching and nutrient runoff. Moreover, its neutral pH and high organic carbon content contribute to soil health and microbial activity. Furthermore, biochar aids in waste management by utilizing agricultural residues as feedstock. However, despite its promising advantages, biochar application requires careful consideration. Variations in feedstock and production methods can influence its efficacy and environmental impact. Moreover, its long-term effects on soil health and crop productivity warrant further research and field trials. It presents a sustainable solution for enhancing agricultural productivity, mitigating climate change, and managing organic waste. However, its optimal utilization necessitates comprehensive understanding, integrated management practices, and ongoing scientific inquiry.

Keywords: Biomass, organic matter, nano biochar, nutrient, soil fertility, soil health

1. INTRODUCTION

While the precise influence of each factor on climate change is uncertain, it's widely recognized that greenhouse gas emissions stand out as one of the primary drivers. In recent years, the surge in human activities has notably escalated the production and release of these gases into the environment [1- 3]. This is mainly due to population growth, rising urbanization, and the socioeconomic advancement of low- and middle-income countries [4]. Certain agricultural practices can contribute to the generation of waste, posing significant risks to human and animal health, ecosystems, biodiversity, and natural resources [5]. An effective method for capturing and isolating carbon involves extracting greenhouse gases from industrial emissions and securely storing them in tanks. Carbon dioxide emissions from soil also detrimentally impact the global carbon cycle and ecosystems. Soil organic carbon (SOC) represents the largest reservoir of carbon, containing twice as much carbon as the atmosphere. The preservation or release of soil organic carbon significantly influences atmospheric carbon dioxide levels. Biochar's role in mitigating CO_2 emissions is through carbon sequestration, where it stores carbon in a stable form, preventing organic matter-derived CO_2 from escaping into the atmosphere. When biochar is created from biomass via pyrolysis, it transforms easily decomposable biomass into long-lasting carbon, which remains in the environment for extended periods, effectively reducing CO_2 emissions. This process contributes to achieving carbon neutrality by absorbing atmospheric CO_2 and storing it in the soil for the long term, thus counteracting greenhouse gas emissions. Additionally, biochar enhances soil quality, promoting better crop yields, water retention, and soil pH balance, which further aids in carbon sequestration and mitigating the impacts of climate change. Biochar, formed by the pyrolysis of biomass feedstocks such as agricultural and forest residues in an oxygen-limited environment, is a carbon-rich material. This technology has captured considerable attention due to its ability to mitigate climate change and enhance soil fertility and health [6]. Initially, biochar production for soil application was suggested as a means of long-term carbon storage by redirecting carbon from rapidly cycling biomass to a slower cycling reservoir within the soil. Furthermore, numerous researchers have noted that biochar can serve as a substitute for adsorbents in eliminating particular types of pollutants, such as heavy metals, vitamins, minerals, and pharmaceuticals, from liquid solutions [7]. Moreover, apart from biochar's long-term carbon storage potential, extensive research conducted over the past decade has aimed to understand its additional effects beyond soil functions. For example, biochar has been found to potentially reduce greenhouse gas emissions, boost agricultural productivity, and enhance microbial, fungal, and mycorrhizal growth, as well as soil characteristics [8,9]. Utilizing biochar has the potential to generate soils that, in their management and efficacy, begin to resemble the fertile *terra preta*, a form of charcoal historically employed to enhance soil fertility[10]. Although derived from organic and natural sources, biochar exhibits resistance to decomposition due to its highly aromatic carbon structure. Consequently, biochar remains a key component in agricultural practices for its capacity to maximize enhance cation exchange [11], along with nutrient obtainability [12], with enhanced water holding capacity [13].

2. AN OVERVIEW OF NANO BIOCHAR

Research has demonstrated the extensive advantages of employing nanoparticles in conjunction with plants for agricultural and food-related purposes [14]. Nano biochar refers to a form of biochar that has been processed or engineered at the nanoscale, typically with particle sizes ranging from 1 to 100 nanometers. This specialized form of biochar offers unique properties and enhanced reactivity due to its increased surface area and altered chemical composition, making it potentially advantageous for various applications, including agriculture, environmental remediation, and energy production. The creation of biochar-based nanocomposites, combining the beneficial features of biochar with various types of nanomaterials, is notably significant. These composite formations often exhibit remarkable enhancements in specific functional groups, pore characteristics, increased surface-active sites, and catalytic degradation efficiency, along with rapid separability[15]. The size of biochar particles falls within the nanometer range, influenced by the method used to create nano biochar, whether it's adjusting the pyrolysis temperature or employing exfoliation techniques, as investigated in numerous recent studies [16,17,18]. Nano biochar was produced from pine wood biochar through a process involving a planetary ball mill. Pre-cooling the biochar at -80°C prior to milling resulted in a particle size reduction of up to 60 nm and increased the surface area of the nano biochar by 15 times compared to the original biochar. The resulting nano biochar can be employed for the adsorption of carbamazepine pesticide from wastewater [19]. Unlike many other nanocomposite materials, distinct criteria exist for utilizing biochar as the substrate material for nanocomposite formation. Primarily, the feedstocks for biochar production are abundant and cost-effective, typically sourced from agricultural biomass and solid waste [10,20]. Micro/nano biochar finds application in a wide array of fields, serving purposes such as plant growth promotion, enhancing plant resilience against stress factors, and remediation of pesticide contamination. Additionally, it can be utilized in soil and water remediation efforts, wastewater treatment, carbon sequestration, and as a component in composite materials for diverse industrial and environmental applications. Its versatile nature and beneficial properties make it valuable across multiple sectors, contributing to sustainability and environmental stewardship initiatives.

3.STEPS INVOLVED IN THE PRODUCTION OF NANO BIOCHAR

Nano Biochar production is a complex process that involves several steps. It is a carbon-rich material produced by heating biomass in an oxygen-limited or oxygen-free environment, a process known as pyrolysis. Nano biochar is a specific form of biochar that has been subjected to additional processing to reduce its particle size to the nanoscale range, typically below 100 nanometres.

3.1Steps involved in nano biochar production are as follows:

1. **Feedstock selection and preparation:** The first step in nano biochar production involves selecting the appropriate biomass feedstock and preparing it for the pyrolysis process. Common feedstocks include agricultural residues like rice husks, wheat straw, and corn stover, as well as forestry residues such as sawdust and wood chips. The feedstock is pre-treated by drying, grinding, or chopping to achieve a uniform particle size and moisture content, which facilitates efficient pyrolysis.
2. **Pyrolysis:** The prepared feedstock is then subjected to pyrolysis, a thermal decomposition process that occurs in the absence of oxygen or with limited oxygen supply. The feedstock is heated to temperatures ranging from 300°C to 700°C in a pyrolysis reactor, which can be either a batch system or a continuous system. During pyrolysis, the biomass undergoes chemical transformations, releasing volatile compounds and leaving behind a solid, carbon-rich residue called biochar. The pyrolysis process also produces bio-oil (a liquid product) and syngas (a gaseous product), which can be collected and utilized for various applications.
3. **Mechanical grinding/milling:** The bulk biochar produced from pyrolysis is then mechanically ground or milled using processes like ball milling to reduce the particle size and produce nano-biochar. The milling process increases the specific surface area and reactivity of the nano-biochar compared to the parent biochar. The rate of temperature increase during milling also affects the structure and porosity of the resulting nano-biochar.These techniques involve applying mechanical force or ultrasonic energy to break down the biochar particles into the nanoscale range, typically below 100 nano meters. The production process may also involve chemical or thermal treatments to modify the surface properties or introduce specific functional groups.

4. **Direct fabrication through flash heating:** In addition to mechanical grinding, nano-biochar can also be directly fabricated through flash heating of the biomass feedstock. This rapid heating process (>1000°C/min) results in the formation of graphitic nanosheets as the nano-biochar product.
5. **Carbonization:** Hydrothermal or flash carbonization of the biomass feedstock can also be used to produce biochar, which can then be further processed into nano-biochar. Carbonization involves the thermal decomposition of the biomass in the presence of limited oxygen, converting it into a carbon-rich solid material
6. **Biochar collection and cooling:** After the pyrolysis process, the biochar is collected from the reactor and allowed to cool down to ambient temperature. Proper cooling is essential to prevent further oxidation and degradation of the biochar.
7. **Sizing and grinding:** The cooled biochar is then subjected to size reduction processes, such as grinding or milling, to achieve the desired particle size range.

Depending on the intended application, the biochar may be ground to a smaller size, ranging from a few microns to a few hundred nano meters.

8. **Purification and stabilization:** After the size reduction process, the nano biochar may undergo purification steps to remove any impurities or unwanted byproducts. Techniques like centrifugation, filtration, or solvent extraction may be employed to separate and purify the Nano biochar. Stabilization techniques, such as surface modifications or encapsulation, may be employed to improve the stability and dispersibility of the Nano Biochar particles in various media.
9. **Characterization and quality control:** The product is thoroughly characterized to ensure its desired properties and quality. Characterization techniques may include particle size analysis, surface area and porosity measurements, elemental analysis, and spectroscopic techniques (e.g., X-ray diffraction, Fourier-transform infrared spectroscopy). Quality control measures are implemented to ensure batch-to-batch consistency and compliance with relevant standards or specifications.

4.STRUCTURAL PROPERTIES OF NANO BIOCHAR

Understanding the physical properties of biochar is essential for comprehending its role in soil and its potential as a means to sequester atmospheric carbon dioxide [21]. Biochar is comprised of carbonaceous material containing polycyclic aromatic hydrocarbons alongside various other functional groups.Some biochars may possess a highly porous structure capable of containing significant quantities of extractable humic and fulvic acids [22] featuring a molecular structure characterized by considerable chemical and microbial stability, biochar exhibits turnover rates influenced by environmental factors over millennia [23]. The varied composition of biochar results in surfaces that can display hydrophilic, hydrophobic, acidic, and basic properties, all of which play roles in their interaction with soil solution substances. The physical and chemical properties of biochar vary depending on factors such as the feedstock material used, the presence of oxygen, and the temperatures reached during pyrolysis[24].

Biochar is derived from polycyclic aromatic hydrocarbons, where six carbon atoms form a ring structure, rendering it resistant to biological and chemical changes. Besides carbon, biochar contains elements like hydrogen and oxygen, and depending on the source material, minerals such as nitrogen, phosphorus, and sulfur may also be present. Functional groups like hydroxyl, ketone, ester, and others contribute to its composition. They often contain significant amounts of humic acids and fulvic organic acids, and their properties can vary from hydrophilic to hydrophobic and from acidic to alkaline based on their composition and level of heterogeneity. These variations allow biochars to interact with both organic and inorganic materials. During the conversion of plant biomass to nano-biochar, the intrinsic structure of the plant, including its vascular system, is preserved, leading to a hierarchical pore structure consisting of macrospores, mesopores, and microspores. Micrometer porosity facilitates air transmission and microbial activity, while also enhancing nutrient storage capacity in the soil through adsorption and desorption processes. The porosity of biochar, which dictates its surface area, exhibits a highly variable pore size distribution ranging from nano- (<0.9 nm), micro- (<2 nm), to macro-pores (>50 nm). The porous structure of biochar is significant as it can serve as a shelter for beneficial organisms like mycorrhizae and bacteria.The porosity and surface area of biochar play crucial roles in determining its nutrient retention capacity through the surface binding of both cations and anions.The specific surface area of nanobiochar surpasses that of clay particles, with properties such as elemental composition, porosity percentage, and particle size being influenced by the thermal decomposition parameters and biomass type. Higher temperatures and longer exposure durations during biomass treatment result in increased nano-biochar production, with the maximum specific surface area typically achieved between 650 and 850°C[25].

5.SOME KEY FEATURES OF NANO BIOCHAR ARE AS FOLLOWS:

Nano-biochar exhibits several unique features that make it a promising material for applications in agriculture and environmental remediation. Some key features of nano-biochar are as follows:

1. **High surface area and porosity:** Nano biochar's nanoscale size grants it an incredibly high surface area-to-volume ratio and a porous structure. This characteristic is pivotal in environmental applications, particularly in soil and water systems. The increased surface area enhances its adsorption capacity, allowing it to effectively trap and retain nutrients, contaminants, and other compounds. This is crucial for soil remediation and water purification efforts, as nano biochar can immobilize harmful substances, preventing them from causing further harm to the environment.
2. **Improved soil fertility and nutrient retention:** Nano biochar's porous structure enables it to adsorb essential plant nutrients like nitrogen, phosphorus, and potassium, gradually releasing them into the soil. This process enhances soil fertility by providing a sustained supply of nutrients to plants, thereby promoting healthy growth. Additionally, the retention of nutrients within the nano-biochar helps reduce nutrient leaching, ensuring that valuable resources are utilized efficiently and minimizing environmental pollution.
3. **Soil amendment and water retention:** The porous nature of nano biochar enhances soil structure, improving aeration and water-holding capacity. This is beneficial for plant growth, as it facilitates root development and nutrient uptake. Moreover, it acts as a reservoir for moisture, reducing water loss through evaporation and enhancing water retention in the soil. This is particularly advantageous in arid regions or during drought periods, where water conservation is critical for sustaining agricultural productivity.
4. **Contaminant adsorption and immobilization:**Its high affinity for adsorbing and immobilizing contaminants makes it an effective tool for environmental remediation. Whether it's heavy metals, pesticides, or other pollutants, nano biochar can capture and trap these harmful substances, preventing them from spreading further in soil and water systems. By sequestering contaminants, nano biochar helps mitigate the adverse effects of pollution, safeguarding ecosystem health and human well-being.
5. **Microbial habitat and nutrient cycling:** The porous structure of nano biochar provides an ideal habitat for beneficial soil microorganisms. These microorganisms play a crucial role in nutrient cycling and soil health maintenance. By fostering microbial activity, it promotes the decomposition of organic matter, nutrient mineralization, and symbiotic relationships with plants, ultimately enhancing soil fertility and productivity. Additionally, the presence of microbes can aid in the degradation of organic pollutants, further contributing to environmental remediation efforts.
6. **Enhanced plant growth and yield:** Nano biochar's multifaceted benefits, including improved soil fertility, water retention, and contaminant immobilization, culminate in enhanced plant growth and crop yields. By creating a favourable environment for plant growth and development, it facilitates optimal nutrient uptake, root proliferation, and stress tolerance. This leads to healthier, more vigorous plants with increased resistance to environmental pressures, ultimately resulting in higher agricultural productivity and food security.
7. **Slow-release fertilizer carrier:** Nano biochar's ability to serve as a carrier for slow-release fertilizers offers several advantages in agricultural practices. By encapsulating nutrients within its porous structure, it enables a controlled and sustained release of fertilizers over time. This reduces nutrient losses through leaching or volatilization, ensuring that plants receive a consistent supply of nutrients without the need for frequent applications. Moreover, the gradual release of nutrients

enhances nutrient efficiency and minimizes environmental impacts, promoting sustainable farming practices.

8. **Wastewater treatment and water purification:**The adsorption properties of nano biochar make it an effective agent for wastewater treatment and water purification. In contaminated water sources, it can adsorb organic and inorganic pollutants, including dyes, heavy metals, and pharmaceuticals, thereby improving water quality. Additionally, it can act as a filter medium or adsorbent in treatment systems, removing contaminants and pathogens from wastewater streams. This contributes to the provision of clean water for various purposes, from agricultural irrigation to drinking water supply, benefiting both human health and the environment.
9. **Carbon sequestration:** Nano-biochar plays a crucial role in carbon sequestration, mitigating greenhouse gas emissions and combating climate change. Derived from renewable biomass sources, It contains stable carbon that remains sequestered in the soil for an extended period. By converting biomass into biochar and incorporating it into soil, carbon dioxide is effectively removed from the atmosphere and stored in a stable form. This not only helps mitigate climate change by reducing atmospheric carbon dioxide levels but also enhances soil carbon stocks, improving soil fertility and resilience to environmental stresses.
10. **Catalytic properties:** Depending on its composition and surface modifications, nano-biochar can exhibit catalytic properties, making it valuable in various chemical processes. For instance, nano-biochar can act as a catalyst in the degradation of organic pollutants, accelerating their breakdown into less harmful substances. Additionally, it can serve as a catalyst in biofuel production processes, facilitating the conversion of biomass into renewable energy sources like bioethanol or biodiesel. This versatility highlights its potential in promoting sustainable energy production and environmental remediation.
11. **Compatibility with other materials:**The compatibility of nano biochar with a wide range of materials allows for the creation of composite materials with enhanced properties for specific applications. By integrating it with polymers, minerals, or nanoparticles, synergistic effects can be achieved, resulting in materials with improved mechanical strength, adsorption capacity, or catalytic activity. These composite materials can be tailored to address specific challenges in agriculture, environmental remediation, or other fields, expanding the potential applications of it and enhancing its effectiveness in diverse contexts.
12. **Sustainable and renewable source:** Derived from renewable biomass sources such as agricultural residues, forestry waste, or organic byproducts, nano biochar represents a sustainable and environmentally friendly material. Its production contributes to the development of a circular bioeconomy, where biomass is utilized efficiently to create value-added products while minimizing waste and environmental impact. By utilizing renewable resources for its production, reliance on non-renewable materials is reduced, leading to greater resource efficiency and long-term environmental sustainability.

These features of nano-biochar highlight its potential for improving agricultural productivity, enhancing soil health, remediating contaminated environments, and contributing to sustainable practices in various sectors, including agriculture, environmental management, and waste treatment.

6. IMPACT OF BIOCHAR ON SOIL MICROORGANISMS

Microbial communities play a vital role in the performance of plant-soil ecosystems, encompassing soil health, fertility, carbon and nutrient cycling, and crop yields[26]. The abiotic processes initiated by biochar, including physical and chemical pathways, can influence the function and diversity of soil microbial communities[27].

Biochar could potentially alter the profile of microbial populations by altering the physical environment of the soil. Moreover, changes induced by biochar in microbial growth might also impact soil physical attributes. These physicochemical variances induced by biochar in soil can significantly impact the prosperity, diversity, and structure of microbial communities, thereby influencing the dynamics of plant-microbe interactions in the soil [28]. Changes in pH and oxidation potential resulting from the presence of biochar in the soil can impact both microbial activity and population structure [29]. The addition of biochar to the soil has the potential to affect the adsorption dynamics of rapidly mineralizable carbon and nutrient fertilizers, leading to alterations in bacterial and fungal community patterns and behaviors [30]. The positive impact of incorporating biochar on microbial activity and communities is attributed to its ability to supply readily degradable organic metabolites and nutrients for microbial growth. Biochar materials with high surface areas and diverse charges facilitate microbial growth and the sorption of nutrient ions. The highly porous structure of biochar can create a conducive microhabitat for soil microbial populations, providing essential organic metabolites and minerals necessary for microbial development. Biochar amendment has been demonstrated to increase soil microbial abundance by providing a favorable habitat for microorganisms, promoting their activity and reproduction. The porous structure of biochar offers shelter for microorganisms, shielding them from harsh conditions and reducing inter-species competition, ultimately leading to a rise in their abundance.

Additionally, biochar utilization of labile carbon and improvements in soil properties such as pH and adhesion contribute to this increase. Moreover, the addition of biochar alters the relative abundance and composition of soil bacteria and fungi, influencing the microbial community structure. Specific bacterial genera like *Sphingomonas, Gemmatimonas, Nitrospira,* and *Pseudomonas* have been found to increase in relative abundance with biochar treatments. These changes are influenced by factors such as soil properties, biochar type, and application duration. Furthermore, biochar application has been associated with enhanced soil microbial diversity, as it modifies the soil microenvironment, fostering conditions conducive to diverse microbial populations. However, the long-term impact of biochar on soil microbiota is influenced by land management practices, especially in cropland soils with frequent fertilization and amendments. Successful soil management strategies involving biochar should consider both biochar properties and existing soil conditions to achieve desired outcomes. Caroline and Komang's publication effectively consolidated the latest research findings, introducing molecular-based DNA techniques to investigate biochar mechanisms for enhancing soil microbial ecology [31]. Understanding the effects of biochar on variations in microbial populations and functions can provide a valuable knowledge base for developing biochar-based systems to improve degraded soils and maintain soil health and plant protection.

7.INFLUENCE OF NANO BIOCHAR ON PLANT GROWTH AND DEVELOPMENT

Recent studies suggest that biochar is more inclined to effectively enhance plant growth in acidic soils compared to alkaline soil types [32]. Biochar has been studied within soil-less fertigation systems, revealing significant benefits in enhancing yields of peppers and tomatoes [33]. There is widespread recognition of the necessity to reduce or eliminate the utilization of peat in horticulture, seeking environmentally friendly and cost-effective sustainable growth mediums. Biochar emerges as a promising alternative to peat [34]. Saxena *et al*. (2014) found that the application of biochar alongside water-soluble carbon nanoparticles significantly enhanced wheat growth [17]. Concerning root growth and development, the application of alkaline biochar rather than acidic biochar can lead to a significant increase in root biomass [35].Nano-biochar exhibits remarkable capabilities in nutrient retention and adsorption due to its elevated specific surface area and porosity. This enables it to effectively capture and hold essential nutrients like nitrogen, phosphorus, and potassium, thereby enhancing their availability for plant uptake, consequently promoting enhanced plant growth and yield. Moreover, nano-biochar acts as an excellent carrier for beneficial plant growth-promoting bacteria, such as *Bacillus megaterium,* facilitating the solubilization of insoluble phosphorus, which further boosts plant growth and health. Additionally, the application of nano-biochar leads to improved soil properties including pH regulation, increased water-holding capacity, and enhanced cation exchange capacity, fostering a conducive environment for plant growth and development. In another study, the utilization of bamboo biochar at concentrations below 10% resulted in nodulation development and enhanced the growth of soybeans [36]. The specific impacts of biochar supplementation on plant dry biomass and nutrition predominantly depended on the type of biochar and the application rate. When soil was amended with coconut husk biochar at a uniform rate of 30 t ha^{-1}, it resulted in a 90% enhancement in maize biomass, with plant nitrogen and phosphorus concentrations reaching 0.88% and 0.12%, respectively. Thus, the enhancement in plant biomass and nutrition underscores the effectiveness of coconut husk biochar as a soil amendment [37].

8.INFLUENCE OF NANO BIOCHAR ON THE PHYSICAL PROPERTIES OF SOIL

The disparity in physical structure between soil and biochar results in alterations in tensile strength, hydrodynamics, and gas flow within the soil, consequently impacting soil organisms. These effects are contingent upon the type and characteristics of the biochar, including its raw material and heat treatment. When the tensile strength of biochar is lower than that of the soil, such as in clay-rich soil, adding biochar reduces the soil's tensile strength. For instance, in a study conducted on Alf sols, the addition of biochar decreased tensile strength from 4.64 to 31 kPa. Reduced mechanical impedance is critical for facilitating root growth, making roots less resistant to soil and enabling easier root development[38-39]. Optimal root growth occurs with around 10% biochar in the growing medium, while further increases beyond 15% do not significantly enhance root growth. This enhancement in root growth also promotes mycorrhizal association and increases soil mineral elements, thus improving seed germination rates. Decreased tensile strength may enhance the mobility and displacement of invertebrates in the soil, contributing to increased soil fertility as they feed on organic matter. The reduction in soil bulk density caused by biochar leads to increased soil porosity, which in turn affects water retention, root development patterns, and soil organisms. This phenomenon can be attributed to the lower density of biochar compared to soil minerals. Biochar contains both macro and micropores, ranging from approximately 1 to over 50 nm in diameter, which exhibit strong resilience to weathering. Consequently, this characteristic significantly decreases the bulk density of biochar within the soil. Research indicates that the density of biochar ranges from 0.09 to 0.5 grams per cubic centimeter, depending on the raw material used. This density is considerably lower than that of soil. The macro and micropores of biochar contribute to its weather resistance and significantly lower bulk density compared to soil minerals. For instance, adding 60 tons per hectare of biochar to soil reduced bulk density by approximately 5.8% [2]

9.INFLUENCE OF NANO BIOCHAR ON CARBON DIOXIDE EMISSIONS FROM SOIL

At the outset, the introduction of biochar into the soil initially results in increased carbon dioxide emissions. For instance, incorporating 8% biochar into the soil leads to elevated carb within the first 20 days. However, over an extended period, particularly after 120 days, gas emissions notably diminish. In essence, the presence of soil biochar over prolonged durations tends to mitigate carbon dioxide emissions. Overall, the release of carbon dioxide from the soil is contingent upon soil conditions, the microbial population, and the physicochemical attributes of the biochar [40-41]. The addition of biochar to the soil can potentially stimulate and enhance the growth of microorganisms by providing a substrate for their proliferation. The micrometric porosity of biochar enhances soil moisture retention, leading to a reduction in the decomposition of soil organic carbon (SOC). Consequently, biochar indirectly mitigates carbon dioxide emissions by promoting increased soil moisture levels [1].

10. ROLE OF BIOCHAR AS PLANT DISEASE CONTROL AGENT

The efficacy of biochar's plant resistance mechanisms relies on eliciting reactions, involving both systemic acquired resistance (SAR) and induced systemic resistance (ISR) pathways. These pathways collectively contribute to a comprehensive management capability in promoting canopy growth in crops [42]. Combining biochar with compost could potentially enhance pathogen resistance, although it poses some risks. This approach is viable because biochar and compost may have complementary abilities to control various soil-borne pathogens. The disease-suppressing properties of compost are multifaceted. Immature composts, in particular, release volatile compounds such as sulfur, organic acids, and ammonia, which contribute to disease reduction. On the other hand, the suppressive effects of mature compost are primarily biological, often involving microbial antagonism or boosting plant host resistance [43]. In comparison to peat media, biochar typically exhibits positive or straightforward effects on plant growth when applied at concentrations exceeding 25%. However, research on the effects of biochar on plant diseases reveals that while lower concentrations (≤1%) of biochar often lead to a reduction in some diseases, higher concentrations (>3%) are largely ineffective or may even exacerbate plant diseases [44]. The ability of biochar fertilizer to stimulate transcriptional changes, along with its interaction with various plant protection pathways, is likely a key factor in its broad-spectrum effectiveness for reducing diseases [45].However, our understanding of biochar's ability to confer systemic resistance to plant pathogens remains incomplete, with only a limited number of studies [46].It is imperative to conduct further research and studies to comprehensively investigate and elucidate this aspect.

10. CONCLUSION

Integration of nano biochar into soil offers a novel approach for long-term atmospheric CO_2 storage, providing a stable carbon sequestration method with minimal risk of carbon return. It enhances soil organic carbon stability, mitigates CO_2 emissions, and improves soil structure, water retention, microbial activity, nutrient availability, soil and plant health while reducing leaching loss. Despite the need for long-term stability investigation, benefits include enhanced water retention in drained soils, landscape rehabilitation, and efficient nutrient absorption by plants. Nano biochar shows promise in saline soil improvement and soil contaminant remediation, contributing to increased plant productivity, reduced pollution, and optimized water and fertilizer usage. Tailored nano biochar development offers further opportunities for sustainable soil management and climate change mitigation.

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